# FORMATION OF EUCRITES AND DIOGENITES ON A VESTA-SIZED ASTEROID: II. EQUILIBRIUM CRYSTALLIZATION OF A CHONDRITIC MAGMA OCEAN.

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**INTRODUCTION:** Having demonstrated that the HED parent body may have a small core that separated during a global magma ocean episode [1], we can now evaluate whether the eucrites and diogenites may represent the residual liquids and cumulates formed during the crystallization of such an ocean. The HED parent body mantle composition will differ from the bulk chondritic composition after separation of an Fe-rich metallic core, even if the core is small. The most important difference will be the Mg/(Mg+Fe) ratio (Mg#) of the mantle material; separation of a metallic core will increase this ratio over the bulk chondritic value, thus having an impact on the composition of phases crystallizing from a magma ocean.

We have used the thermodynamics-based computer program MELTS [2] to consider the cooling histories (fractional or equilibrium crystallization) of the possible mantle compositions (bulk chondrite minus core) calculated by [1]. One interesting feature of all the *fractional* crystallization trends is that they become too FeO-rich at the eucritic $SiO_2$ and MgO contents, thus indicating that fractional crystallization of a chondritic magma ocean cannot produce a eucritic residual liquid. The liquids produced by *equilibrium* crystallization all come closer to eucritic liquids at 80 to 85% crystallization. We will show that a molten mantle originating from ordinary chondrite material (0.75L+0.25H) could be the initial magma composition leading to both the diogenite cumulates and the eucritic basalts and cumulates.

## A MODEL FOR THE EUCRITES

***Equilibrium crystallization of an ordinary chondrite magma ocean:*** Olivine, spinel and low Ca-pyroxene are stable crystallizing phases from 1510 to ~1230 _C (P < 1.5 kb), at which point olivine becomes unstable and reacts with the liquid to form pyroxene. From 1220 to 1190 _C, low Ca-pyroxene and spinel crystallize while olivine is resorbed - these are the phases present in diogenites. Residual liquids at 1240 to 1220 _C are similar in major element composition to primitive eucrites (Fig. 1). A fundamental point of contention in past models for diogenite genesis has been whether the Mg# of the proposed fractionated minerals (cumulates) can be reconciled with the Mg# of the cumulate diogenites and (e.g., [3-6]). The Mg#'s of the orthopyroxene crystallizing to form the ordinary eucrite liquids show nearly complete overlap with the range of Mg# in pyroxene from diogenites (0.70 to 0.76).

Further constraints are provided by consideration of trace elements (compatible: Sc, V and Cr; incompatible: Ba, Sr, Zr, Y, REE and Lu). If equilibrium crystallization of olivine, orthopyroxene and spinel from a chondritic magma ocean can account for the ordinary eucrites, then the trace elements in the residual liquid should be consistent with the following mass balance:

$$C(liq) = C_o / [X(liq) + X(oliv)*D(oliv/liq) + X(opx)*D(opx/liq) + X(sp)*D(sp/liq),$$

where $C_o$ is the initial chondritic abundance of the element and X is the mass fraction of each phase. Using the average ordinary chondrite elemental abundances tabulated by [7], the calculated mass fractions of liquid, olivine, orthopyroxene and spinel from the previous section, and partition coefficient data from [8,9], the concentration of these elements in the residual liquid can be calculated. Comparison of these calculated values to the measured abundances in ordinary eucrites, indicates that all 12 elements are consistent with the major element modeling.

***Convective lock-up and extrusion of liquids:*** During a terrestrial magma ocean stage, crystals can be suspended in a convecting solid-liquid mush until a critical melt fraction is attained (20 to 40%), whereby the viscosity becomes large enough that gravitational separation of solid from liquid silicate ensues [10-12]. For a smaller body such as Vesta, however, the gravitational force is much smaller (~0.3 $m/s^2$), and thus the critical melt fraction is likely to be < 20% [12]. For a Vesta-sized body undergoing equilibrium crystallization, once a melt fraction of approximately 15% is attained, crystals will lock up and melt will extrude as a residual liquid to the surface. Thus a crudely layered mantle is formed which is dominated by dunite at depth and grades upwards into harzburgite (diogenite) and basalt (eucrites) at the surface. The extruded residual liquid, as shown above, has a composition like the most primitive ordinary eucrites.

***Fractionation of Main Group eucrites to produce cumulates and Nuevo Laredo trend liquids:*** Once the ordinary eucrite liquids are extruded at the surface and, perhaps, intruded into a thin solid crustal layer (e.g., [13]), they can then fractionate to form the Nuevo Laredo trend eucrites and the corresponding cumulate eucrites. Previous workers have noted several lines of evidence for a fractionation trend in eucrites with Nuevo Laredo representing a more fractionated melt [14,15]. Using the MELTS program [2] two residual liquid compositions (1220 and 1240 _C) have been cooled along a fractionation path showing the evolution of the residual liquids (Fig. 1). These trends closely match the range of evolved eucrites, especially with respect to the $Al_2O_3$ and MgO contents. The range of Mg# of crystallizing pyroxene produced in such fractionation trends entirely overlaps the range of Mg#'s of pyroxene from the cumulate eucrites (0.65 to 0.40).

***Gardening and ejection of material from the HED parent body***

The predicted crystallization sequence of *equilibrium* crystallization in a magma ocean will produce a layered mantle and basaltic crust. Estimates of the thicknesses of these layers for a Vesta-sized body may be made from the equilibrium crystallization calculations. After 89% equilibrium crystallization of the magma ocean (cooling from 1510 _C to 1220 _C), olivine (36.7%), pyroxene (50.6%) and spinel (1.4%) would be present with 11 % melt; complete segregation of melt from crystals at this point (highly likely from a convective point of view) would result in a solid mantle out to a radius of 238 km, with a 12 km thick outer layer of basaltic residue. Cooling from 1220 to 1190 _C would result in the resorption of olivine to form pyroxene, with 5% liquid left. Given these layering constraints it is clear that impacts could easily excavate and penetrate the thin eucritic crust to expose diogenitic material below [16]. The ejection of km-sized chunks of Vesta could be achieved by a 10-20 km-sized impactor, at a velocity of 8 km/s, without disrupting or destroying Vesta [17].

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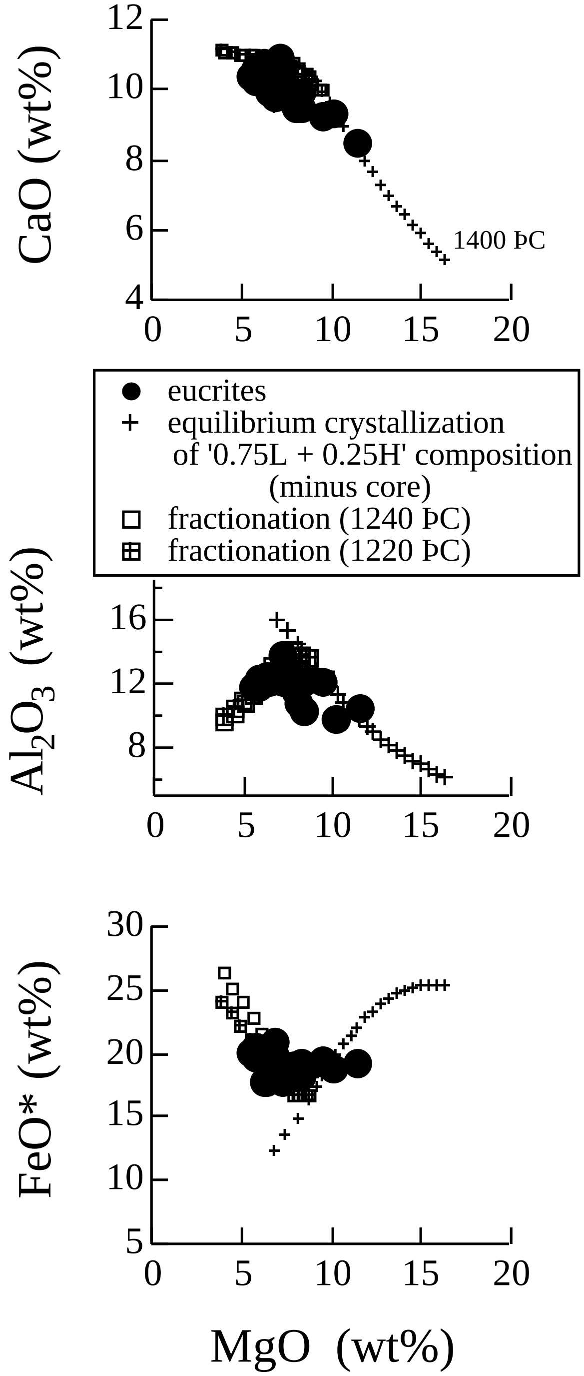


Figure 1: Results of equilibrium crystallization calculations for '0.75L + 0.25H' (minus core) mixture. Symbols for calculations represent 10 _C intervals.